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Effect of glass fiber on the permanent deformation of numerically modelled wearing courses in ANSYS

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Abstract*– The continuous increase in the number of heavy vehicles usually causes the wearing course to present greater permanent deformation in less time, due to its low resistance to traffic loads. Given this, several studies carried out in the laboratory have tried to reduce the permanent deformation using additives such as glass fiber. That is why this work analyses the effect of glass fiber on the permanent deformation of wearing courses using ANSYS. First, the mechanical properties of asphalt mixtures with different percentages of glass fiber were compiled in order to create materials that represent each mixture in ANSYS. Then, the simulation of the Marshall stability and flow test was carried out to configure the materials created. Finally, materials were evaluated in the wearing course model created and the permanent deformation associated with each one of them was obtained. The results showed that glass fiber reduces the permanent deformation of the wearing course by an average of 15%, unlike mixtures without fibers. In addition, it was concluded that the ideal fiber content that could be used to improve the resistance of wearing courses to permanent deformation is between 0.25% - 0.40% glass fiber.

Keywords—permanent deformation, glass fiber, wearing course, numerical model, ANSYS.

I. INTRODUCTION

In flexible pavements, the wearing course is the layer that is located on the surface of the entire structure; therefore, it is directly exposed to severe conditions imposed by traffic and weather [1]. The main mechanism of damage or failure experienced by the wearing course, and must be considered in the mixture design, is permanent deformation, since it affects both the useful life of the structure and the safety of users [2], [3]. This phenomenon consists of the accumulation of non-recoverable deformation during load and unload cycles. In fact, the appearance of deformation on the wearing course is a product of its low resistance to heavy loads. That is why the damage is accentuated with the repeated passage of vehicles [4]. So, vehicular traffic influences permanent deformation not only by its weight or magnitude, but also by its frequency [5].

At present, wearing courses are subjected to excessive demand, due to the rapid growth of traffic and heavy vehicular overload [6]. For this reason, the permanent deformation occurs prematurely or to a greater extent on the wearing course, so that the performance during its useful life is affected [7]. For instance, it has been shown that the asphalt layer is commonly damaged by permanent deformation because its characteristics have low resistance to this phenomenon [5]. In general, many studies agree that wearing course must be reinforced to improve its performance against deformation [6]–[8].

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The use of natural and synthetic fibers is an appropriate reinforcement alternative to produce wearing courses, because it improves different properties of asphalt mixtures [9]. There are many works that have carried out laboratory tests with asphalt mixtures incorporating different types of fibers. These emphasize that the improvement of properties is evident, but most agree that glass fiber presents better results [10], [11]. For example, the asphalt mixture modified with 0.25% glass fiber with a length of 10 mm reduces permanent deformation by 20% [6]. Another study showed that it is important to consider the length of the fiber used because the results shown by the asphalt mixture prepared with 0.4% glass macrofiber of 36 mm length, reduced permanent deformation by 48% [8]. According to this, it is evident that the ideal percentage of glass fiber is not the same for both cases, due to multiple factors such as the origin and quality of the materials, the form of mixture production, type of asphalt binder, and others.

On the other hand, some authors have innovated in the field of engineering since they have generated numerical models in ANSYS to obtain the permanent deformation of wearing courses. The main idea is to configure mechanical properties, type of load and other conditions to which the layer will be subjected [12], [13]. This can be validated in recent publications on the subject, including a study that compared the permanent deformation obtained computationally and experimentally and highlighted that the model only presents a slight difference with respect to laboratory tests [7].

For these reasons, this work compiles results from studies that produced asphalt mixtures with glass fibers. After this, ANSYS is used to simulate the Marshall test and to be able to configure the asphalt mixtures. Then, in the same software, the numerical model of the wearing course is created, and the analysis conditions are established. Later, the model is solved, and the deformation is obtained. Finally, the results obtained in the wearing course model for each case are recorded.

This work analyses the effect of glass fiber on permanent deformation, by incorporating different percentages of fiber in the composition of asphalt mixtures. This is verified with a numerical model of wearing course subjected to cyclic loading in three cases. Each case uses the results of asphalt mixtures with glass fibers, taken from own investigation and two external studies. Therefore, percentage range of glass fiber is determined that could improve response to permanent deformation for any case of wearing course, when a value within the range is used.

II. METHODOLOGY

This section details the process that was carried out to define the effect of glass fibers on the permanent deformation of wearing courses. First, the properties of asphalt mixtures are compiled. Then, the model simulating the Marshall Stability and Flow test is created to represent each asphalt mixture as a material in ANSYS. That is why the properties of each asphalt mixture are set up in the model. The Marshall Stability and Flow test model was created according to the international standard ASTM D6927. Next, the wearing course model subjected to load is created and the deformation associated with each material is obtained. Finally, the results are examined and compared with the results of the compiled studies to analyse the effect of glass fiber and determine the ideal percentage range. Fig. 1 presents the flowchart of the research.

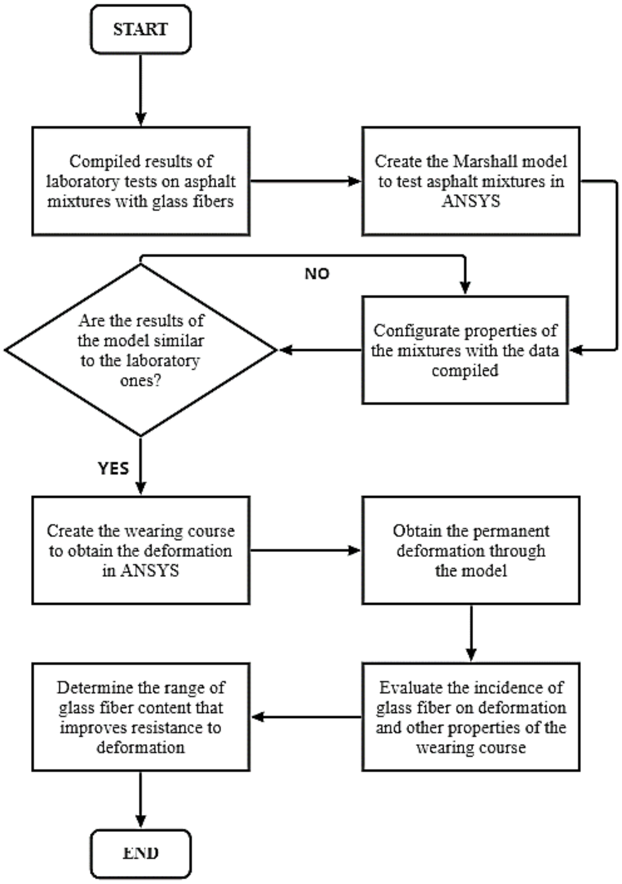

Fig. 1 Methodology implemented in the research.

III. MATERIALS AND TOOLS

Three cases of wearing course were analysed to evaluate the effect of glass fiber on permanent deformation. In each case, laboratory results of asphalt mixtures with glass fibers from previous studies are used. The results of the first case were compiled from the research carried out by the authors of this work. The second case consists of the results obtained by Morea & Zerbino [8], while the third case of Eisa, Basiouny & Daloob [6]. Table I shows the materials used in each case.

TABLE I
MATERIALS USED IN EACH CASE OF ASPHALT MIXTURE

Materials	Wearing course cases		
	1	2	3
Asphalt	PEN 60/70	PG 64-16	PEN 60/70
Aggregate	Crushed stone Romaña quarry Crushed sand Romaña quarry	Stone (6-20 and 6-12 mm) Crushed sand (0-6mm)	Crushed stone ATAKA quarry Crushed sand FAYED quarry
Mineral Filler	Filler	-	Filler

[a] The information used in the table has been taken from [6], [8].

Tables II, III and IV show the properties of asphalt mixture by percentage of glass fiber in cases 1, 2 and 3, respectively.

TABLE II
PROPERTIES OF ASPHALT MIXTURE OF THE CASE 1

Property	Glass fiber percentage	
	0.0%	0.4%
Density (g/cm3)	2.376	2.338
Air Voids (%)	4.50	4.70
Stability (kN)	12.25	11.65
Flow (mm)	3.47	3.17

TABLE III
PROPERTIES OF ASPHALT MIXTURE OF THE CASE 2

Property	Glass fiber percentage			
	0.0%	0.2%	0.4%	0.6%
Density (g/cm3)	2.428	2.411	2.407	2.390
Air voids (%)	4.40	4.50	4.40	5.60
Stabiliy (kN)	17.90	19.40	18.10	19.30
Flow (mm)	4.20	5.00	5.20	5.90

[b] The information used in the table has been taken from [8].

TABLE IV
PROPERTIES OF ASPHALT MIXTURE OF THE CASE 3

Property	Glass fiber percentage				
	0.0%	0.25%	0.50%	0.75%	1.00%
Density (g/cm3)	2.327	2.394	2.358	2.367	2.305
Air voids (%)	3.77	3.40	3.54	3.62	4.20
Stability (kN)	14.45	16.15	15.61	15.47	14.26
Flow (mm)	3.80	3.30	3.40	3.60	4.10

[c] The information used in the table has been taken from [6].

The creation of numerical models was carried out in ANSYS, since it predicts the deformation of elements under the required analysis configuration using the finite element method. The modelling in ANSYS was divided into two stages.

In the first stage, the model that simulates the Marshall Stability and Flow test was created to represent the properties of each asphalt mixture as a material in the software. This means that when the model is solved with an assigned material (mixture) subjected to a certain load (Stability), a deformation equal to the Flow must be obtained. The geometry of the model meets the dimensions required in ASTM D6927. Each material presents density and isotropic elasticity (Young's modulus, Poisson's ratio, Bulk, and shear modulus) as properties. The density was obtained from the asphalt mixture properties of each case, and the Poisson's ratio was established at 0.35, since this value is commonly used for asphalt mixtures [14].

On the other hand, the Young's modulus was obtained through iterations carried out in the model, that is, its value was changed until the deformation in ANSYS is equal to the Flow. The Bulk and shear modulus were obtained by placing the Young's modulus and Poisson's ratio. In addition, the analysis system used in the model was Static Structural, the applied load was equal to the Stability, and the boundary condition was set as fixed at the bottom of the model. This stage concluded with obtaining deformation (Flow) in the model and the correctly adjusted properties. Fig. 2 shows the geometry of the Marshall Stability and Flow test model in ANSYS.

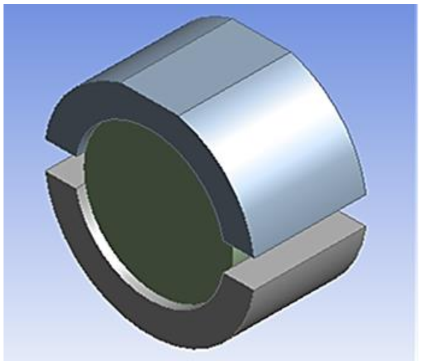

Fig. 2 Geometry of the Marshall Stability and Flow test model.

In the second stage, the numerical model that represents the wearing course was created, whose dimensions were 60x70x10 cm. The wearing course model used the Transient Structural analysis system. In addition, the weight of 80 kN exerted by an equivalent dual–wheel axle was applied and removed for 100 cycles, so that the model experiences the loading and unloading effect as in a real situation. It is important to highlight that the load was applied in the area that generates contact between the tire and the wearing course. The contact area was determined using the equation presented by Gallardo & Sáenz [15]. The radius "r" is calculated with the load value "q", tire pressure "po" and the constant π (1).

$$r = ((q)/(po* \pi))^\wedge 1/2 \qquad (1)$$

In this case, the load exerted by a dual–wheel axle at each contact is 20 kN, and the tire pressure is 600 kPa. This results in a circular contact area with radius 10.4 cm and spaced 35.0 cm from the centre of each area. It is worth mentioning that the model analyses one end of the dual–wheel axle, therefore, there are only two contact areas on the wearing course. Regarding the configuration of the analysis, the contact between tire and wearing course was set as "bonded", the lateral and lower faces were fixed support, and the load of 20 kN and 0 kN were exerted cyclically. Each load was applied for 1 second, so the model was subjected to 100 cycles in 200 seconds. No more cycles were analysed because processing in ANSYS takes a long time. Fig. 3 shows the wearing course model with the configuration of loads and boundary conditions.

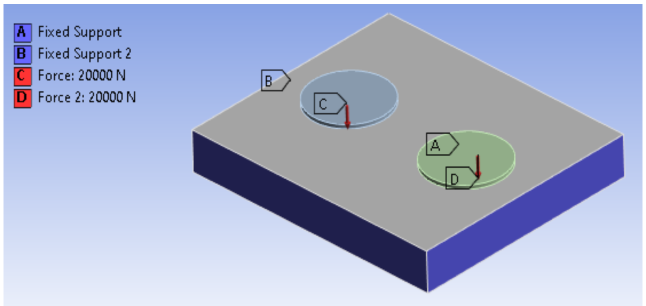

Fig. 3 Configuration of the wearing course model.

IV. RESULTS

A. Results of the Marshall Stability and Flow test model

The asphalt mixtures in case 1 were prepared with 0.00% and 0.40% glass fiber, in case 2 with 0.00%, 0.20%, 0.40% and 0.60% glass fiber, and in case 3 with 0.00%, 0.25%, 0.50 %, 0.75% and 1.00% glass fiber. Each asphalt mixture obtained a deformation in the ANSYS model, which represents the Flow property. Fig. 4 shows the deformation of the Marshall test model of the asphalt mixture with 0.40% glass fiber of case 1. Fig. 5 shows the deformation of the Marshall test model of the asphalt mixture with 0.20% glass fiber of the case 2.

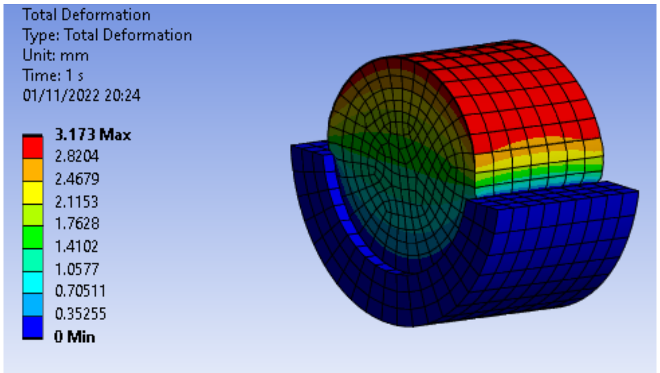

Fig. 4 Deformation of the Marshall test model with 0.40% glass fiber.

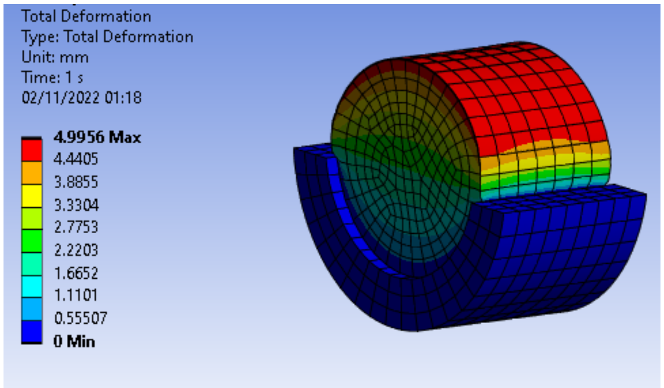

Fig. 5 Deformation of the Marshall test model with 0.20% glass fiber.

Table V shows the results of deformation obtained using the Marshall Stability and Flow test model in ANSYS.

TABLE V
RESULTS OF THE MARSHALL STABILITY AND FLOW TEST MODEL

Case	Glass fiber (%)	Results in ANSYS	
		Stability (kN)	Flow (mm)
1	0.00	12.25	3.4698
	0.40	11.65	3.1730
2	0.00	17.90	4.2053
	0.20	19.40	4.9956
	0.40	18.10	5.2012
	0.60	19.30	5.9054
3	0.00	14.45	3.7999
	0.25	16.15	3.2946
	0.50	15.61	3.4013
	0.75	15.47	3.6003
	1.00	14.26	4.0977

B. Results of the wearing course model

Fig. 6 shows the deformation of the wearing course model of the asphalt mixture with 0.40% glass fiber of case 1. Fig. 7 shows the deformation of the wearing course model of the asphalt mixture with 0.50% glass fiber of case 3.

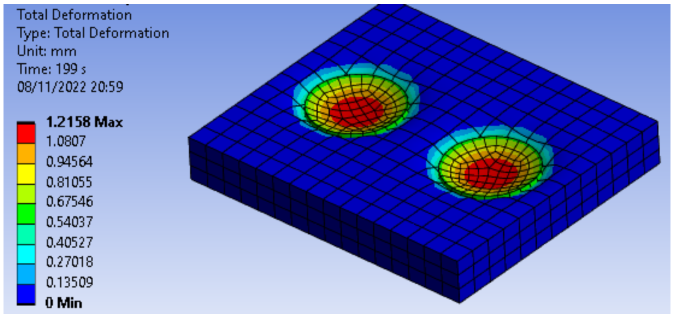

Fig. 6 Deformation of the wearing course model with 0.40% glass fiber.

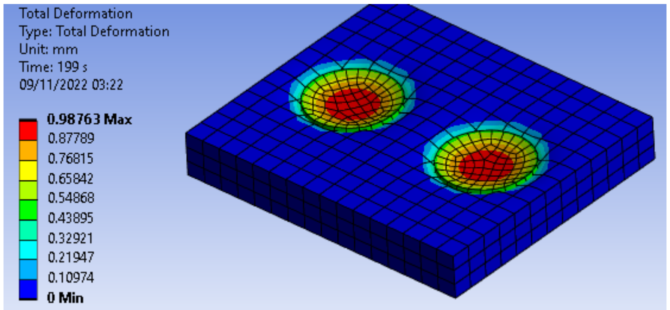

Fig. 7 Deformation of the wearing course model with 0.50% glass fiber.

Table VI shows the results of deformation obtained using the wearing course model in ANSYS.

TABLE VI
RESULTS OF THE WEARING COURSE MODEL

Case	Glass fiber (%)	Deformation (mm)
1	0.00	1.2617
	0.40	1.2158
2	0.00	1.0587
	0.20	1.1534
	0.40	1.2790
	0.60	1.3576
3	0.00	1.1763
	0.25	0.9299
	0.50	0.9876
	0.75	1.0495
	1.00	1.2790

V. VALIDATION

The properties of each asphalt mixture were configured using the Marshall Stability and Flow test model, that is, materials were created and then evaluated with the model to represent the behaviour of the mixtures in ANSYS. Table VII shows the Flow results obtained in ANSYS and laboratory, as well as the variation between them. It is observed that the variations between the flow obtained with the ANSYS model and in the laboratory are almost null. Therefore, the materials created for each mixture are validated, since the deformation (flow) in ANSYS was almost equal to the laboratory values.

TABLE VII
FLOW RESULTS IN ANSYS AND LABORATORY

Case	Glass fiber (%)	Stability (kN)	Flow (mm)		Var.
			ANSYS	Lab.	
1	0.00	12.25	3.4698	3.4700	0.0002
	0.40	11.65	3.1730	3.1700	0.0030
2	0.00	17.90	4.2053	4.2000	0.0053
	0.20	19.40	4.9956	5.0000	0.0044
	0.40	18.10	5.2012	5.2000	0.0012
	0.60	19.30	5.9054	5.9000	0.0054
3	0.00	14.45	3.7999	3.8000	0.0001
	0.25	16.15	3.2946	3.3000	0.0054
	0.50	15.61	3.4013	3.4000	0.0013
	0.75	15.47	3.6003	3.6000	0.0003
	1.00	14.26	4.0977	4.1000	0.0023

V. ANALYSIS AND INTERPRETATION

A. *Stability and Flow of asphalt mixtures*

Glass fiber not only modifies the deformation behaviour of the wearing course, but also other properties. Fig. 8 shows the stability of the asphalt mixture by percentage of glass fiber in each case. It is observed that cases 2 and 3 present a noticeable tendency because as the glass fiber content increase, especially in the range of 0.20% – 0.75%, the stability of the mixture increases. This means that the load required to reach failure in the mixture is greater. Additionally, asphalt mixtures in case 2 showed the highest stability values. On the other hand, case 1 presents a different tendency since as the glass fiber content increases, the stability of the asphalt mixture decreases slightly. However, if the asphalt mixture has high stability and flow, it could be a soft mixture since permanent deformation is due to the viscoplastic flow of the asphalt mixture as mentioned by Huamán & Chang [4]. Therefore, it is necessary to analyse both stability and flow to determine if the improvement of the asphalt mixture is significant.

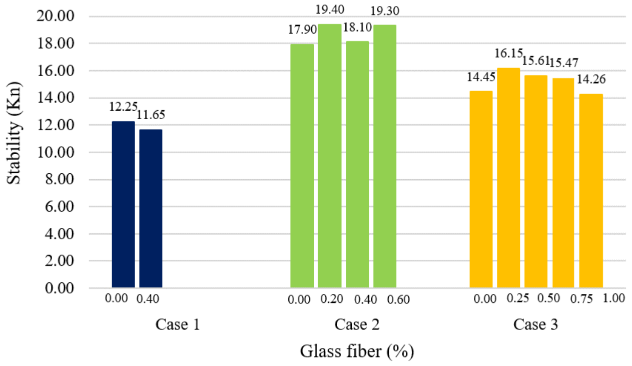

Fig. 8 Stability of the asphalt mixture by percentage of glass fiber.

Fig. 9 shows the flow of the asphalt mixture by percentage of glass fiber in each case. It can be seen in cases 1 and 3 that the flow tends to reduce as the glass fiber content in the asphalt mixture increases, in the range of 0.25% – 0.75%. On the other hand, the flow in case 2 increases as the glass fiber content is higher, and it could be a soft mixture. Therefore, it would be expected that the permanent deformation be higher for this case, compared to the others. Moreover, it can be observed in case 3 that the stability and flow values are inversely proportional, which could lead to mixtures more resistant than conventional.

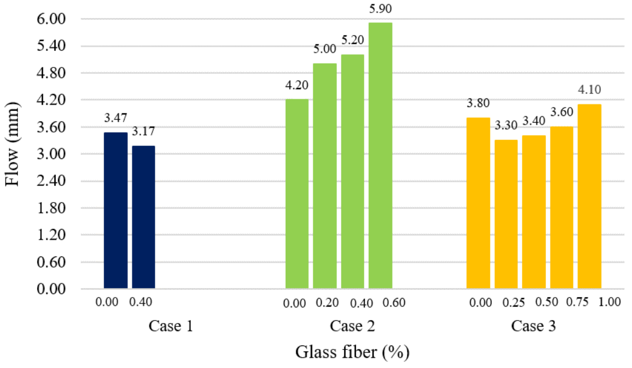

Fig. 9 Flow of the asphalt mixture by percentage of glass fiber.

B. *Permanent deformation of the wearing course model*

The deformation of the wearing course by percentage of glass fiber can be seen in Fig. 10. It is observed that the deformation of the wearing course in cases 1 and 3 decreases when adding glass fiber to the asphalt mixture. In case 3, the deformation increases as the percentage of glass fiber is higher, but still lower than the mixture without fiber, except the asphalt mixture with 1.00% glass fiber. On the contrary, case 2 shows that the addition of glass fiber in the mixture leads to greater deformation of the wearing course model. It could be due to the flow of the asphalt mixtures prepared in case 2 was very high, compared to cases 1 and 3 which meet the permissible limits according to local specifications. The high stability of the mixtures in case 2 did not imply better behaviour to permanent deformation because not only stability increased, but also flow.

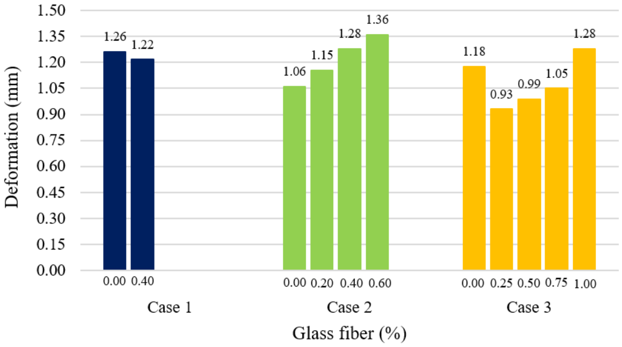

Fig. 10 Deformation of the wearing course by percentage of glass fiber.

Regarding the appropriate glass fiber content, the asphalt mixture with 0.40% glass fiber of case 1 reduced in 4% the deformation of the wearing course, compared to the mixture without fiber. In case 2, the asphalt mixture with 0.20% glass fiber presented less deformation than mixtures with 0.40% and 0.60%. In case 3, the asphalt mixtures with 0.25% and 0.50% reduced the deformation in 26% and 19%, respectively.

It is important to note that the reduction of deformation on the wearing course is due to the glass fiber because it acts as a bridge transferring and limiting stresses, and its distribution produces greater cohesion in the asphalt mixture as concluded by Morea & Zerbino [8], Ziari & Moniri [16] and Park, Shoukat, Yoo & Lee [17]. Therefore, the addition of glass fiber in the asphalt mixture produces less concentration of stresses and greater resistance to repeated loading.

V. CONCLUSIONS

The addition of glass fiber in the composition of asphalt mixtures reduces the permanent deformation on the wearing course. This was concluded by evaluating asphalt mixtures with different percentages of glass fiber in the wearing course model. The results are aligned with those from other studies, which indicate that glass fiber acts as a bridge transferring stresses.

The results of the wearing course model suggest that the percentage of glass fiber that could be used in the asphalt mixture to improve resistance to permanent deformation is between 0.25% – 0.40%. Because the asphalt mixture with 0.25% and 0.40% glass fiber reduced deformation on the wearing course model by 26% and 4%, respectively.

The relation between glass fiber length and deformation was not very clear because cases 1 and 3 presented reduction in deformation. In case 1 and 2, glass fiber of 36 mm in length was used while in case 3 of 10 mm. However, the deformation was considerably reduced in case 3, so it seems that short glass fiber could be a better option.

It was also evidenced that the resistance to deformation of the wearing course could be predicted by comparing the results of stability and flow. For example, asphalt mixtures with high stability and low flow obtained less deformation in the wearing course model, such as the mixture with 0.25% glass fiber that increased stability by 11% and reduced flow by 15%. However, deformation increased in mixtures with high stability and flow

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